Hybrid Energy Storage Based on Supercapacitors and Conventional Batteries System for Nanosatellite Applications

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INTRODUCTION

Nanosatellites have gained considerable attention due to the rapid progress in space technology and the growing need for affordable small-scale satellite missions. These small satellites, usually under 10 kilograms in weight, have the ability to carry out various scientific, commercial, and military tasks. One of the main obstacles to creating and running nanosatellites is the need for energy storage systems that are both effective and dependable.
Generally, the electrical power system of nanosatellite includes photovoltaics for power generation and DC/DC converters to extract maximum power, a battery unit for storage energy, and a distribution unit. This design is commonly appropriate for missions that have low-power
consumption components. Nevertheless, certain CubeSat missions are geared towards investigation and exploration, necessitating the use of high-power payloads such as, imaging equipment, radars, SARs, and communications components like transceivers.
These components require high power over short durations. In such situations, batteries must deliver current exceeding their rated capacity. The high current demand can impact battery life cycles, particularly when the C-rate is exceptionally high, a factor dependent on the mission's load requirements.
Consequently, many researchers are interested in supercapacitors. The European Space Agency (ESA) has been interested in the study of supercapacitors since the beginning of the 2000s. Numerous activities have been initiated to explore the advantages of integrating supercapacitors into spacecraft energy storage systems [1, 2]. They have the ability to provide high power at low volume and mass with a very high charge/discharge cycle [3]. With the growing interest in supercapacitors, several topologies are proposed for their use. Depending on the payload and the mission, they can be combined with the traditional battery or connected separately with a specific subsystem.
Therefore, to study supercapacitor applications, one of the main aspects that should not be neglected is modeling [4], which enables integration into systems.
To overcome the limitations of conventional batteries and supercapacitors, hybrid energy storage systems (HESS) have been proposed. It combines the high energy density of batteries with the high-power density and longevity of supercapacitors, which can enhance the overall performance, reliability, and lifespan of the energy storage system, making it particularly attractive for nanosatellite applications.
In summary, there is an interest in using the supercapacitor in an energy storage system in order to benefit from their high-power density, wider temperature range, and long cycle life.
Therefore, in this paper, we present an experiment that shows the support of supercapacitors during high-power demand for a nanosatellite, first, we study the energy storage system of a 1U nanosatellite designed for high power loads. The second section defines the elements of the energy storage system and the energy requirements. The third section focuses on the modeling and parameter identification of supercapacitors and its importance in determining the real state of charge. Finally, the proposed hybrid system and its results are presented.

ENERGY STORAGE SYSTEM

The energy storage unit provides the power for nanosatellite satellite subsystems and payloads in short missions or backup power for longer missions. All spacecraft that has PV power or solar thermal as a power source require a unit to store energy during eclipse periods and peak-power demands. Typically, storage technologies include batteries. [5]
A battery is made of individual cells connected in series or parallel in order to comply with the bus voltage requirements and current demand. Sustained progress in advanced energy storage systems allows potentially deep space missions with more developed payloads, which necessitates higher energy for its communication systems and science payloads [6].

Energy Requirements

Building on a previous study [8] that designed a power system for a 1U nanosatellite in a Sun-Synchronous Orbit (SSO) with an altitude of 500 km and a Local Time of the Descending Node (LTDN) of 10:30 AM, where there are three different mission power modes, a common mode, a mission mode, and communication, the minimum power for each mode is 0.605 W , 1.125W and 0.875 W respectively. This research investigates a modified scenario. In this case, the

payload was adjusted to consume a higher amount of power estimated at 4.8 W with a 20% of margin over a shorter duration during mission mode in eclipse time, as illustrated in figure 1.
This increased power demand in a brief period requires an efficient energy storage, hence the need to add a supercapacitor in a hybrid with the battery [7]. This will prevent the battery from discharging with a high current, ensuring a high cycle life for the battery.

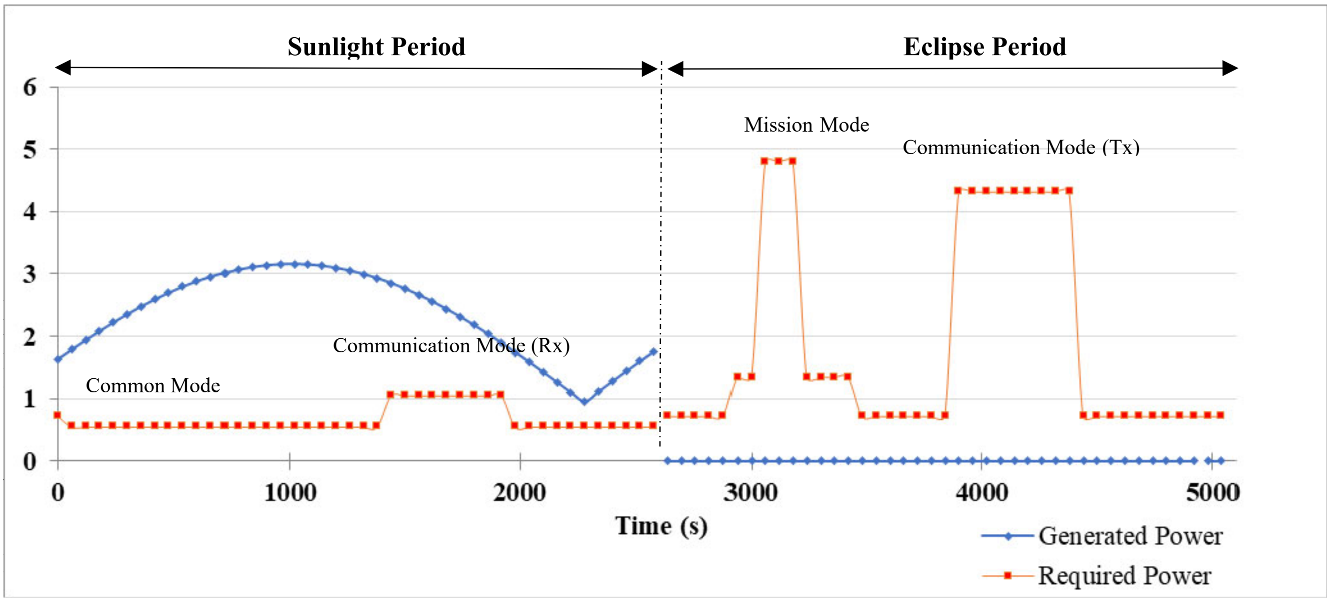

Fig. 1. Power generated and required profile

SUPERCAPACITOR MODEL

Modeling is necessary for supercapacitor systems in order to integrate into a hybrid system and predict their behavior. The simple form of the supercapacitor equivalent circuit is composed of a parallel RC branch connected in series with a resistor [1], where the resistor represents the equivalent series resistance (ESR) and the RC branch represents the self-discharging and capacitance effects. This circuit captures the behavior of supercapacitors within the range of seconds, but for applications operating in the range of minutes or hours, a two-branch model is more accurate.

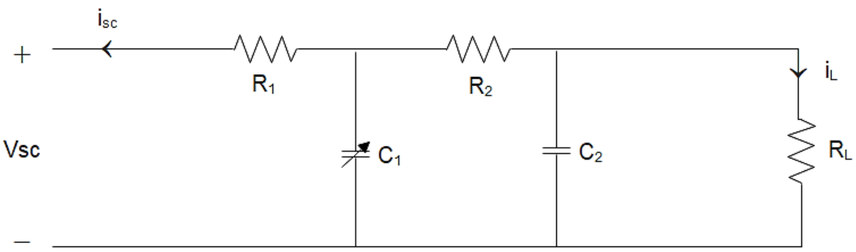

Fig. 2. Equivalent circuit of "two-branch" Supercapacitor model

The equivalent circuit of a two-branch supercapacitor cell is presented in figure 2, it consists of the main branch which corresponds to the immediate response during the charge or discharge phase in the range of seconds, the voltage V1 of the capacitor C1 is:

$$V_1 = \frac{-C_0 + \sqrt{C_0^2 + 2C_0 Q_1}}{C_v} \quad (1)$$

And the instantaneous charge of C1 is expressed by:

$$Q_1 = C_0 V_1 + \frac{1}{2} C_v V_1^2 \quad (2)$$

And the slow branch determines the internal energy distribution at the end of charge or discharge in the range of minutes, the voltage V_2 I expressed by:

$$V_2 = \frac{1}{C_2}\int i_2 dt = \frac{1}{C_2}\int \frac{1}{R_2}(V_1 - V_2)\, dt \qquad (3)$$

V_{sc} and i_{sc} are the supercapacitor voltage and current of the cell respectively, the mathematical equation is given in (4).

$$V_{sc} = V_1 + R_1 I_{sc} \qquad (4)$$

$$V_{sc} = V_1 = \frac{-C_0 + \sqrt{C_0^2 + 2C_0 Q_1}}{C_v} + R_1 I_{sc} \qquad (5)$$

Supercapacitor's Parameters Identification

To identify the parameters of the supercapacitor an experimental set up was implemented using a 2.7v 100F supercapacitor from green-cap, its specifications are reported in Table 1.

Table 1. Supercapacitor specifications

Parameter:	Value	Unit
Rated Voltage	2.7	V
Rated Capacitance	100	F
AC Impedance (1khz)	7	mΩ
DC Resistance	9	mΩ
Maximum Peak Current (1s)	71	A
Leakage Current	0.27	mA
Max Continuous Current	6.5	A

The test bench comprises a power generator model KORAKD-KA3305P (specification in Table.2) to supply the supercapacitor with a constant current, the discharging is assured by the programable electronic load (Table.3), TEKTRONIX MDO3022 oscilloscope for waveform visualization, the procedure followed is summarize in figure 3. The acquisition of the voltage measurements was assured by LabVIEW interface.

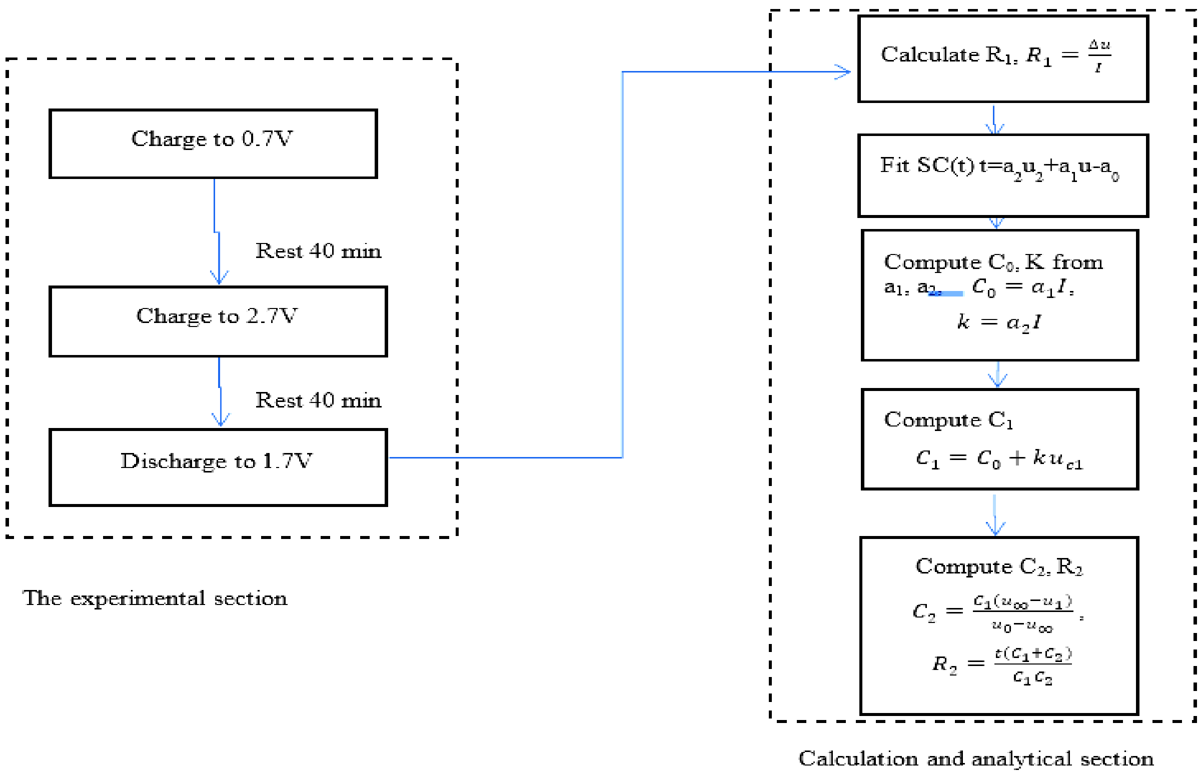

Fig.3. Block diagram of procedure for parameters identification

Table 2. KORAD-KA3305P Programmable DC Power Supply

	Current	Voltage
Rate **Accuracy**	*0-10A* *≤0.1%+5mA*	*0-30V* *≤0.01%+3mV*

Table 3. REK- RK8510 DC electronic load

	Current	Voltage
Rate **Accuracy**	*0-20A* *±(0.05+0.05%FNS)*	*0-150V* *(0.05%+0.025%FS)*

The parameters values obtained are:

$t = 4{,}0531u^2 + 39{,}5\text{u} - 0{,}357$

$R_1 = 0{,}01\Omega$

$C_0 = 79F$

$C_1 = 92{,}942F$

$C_2 = 3{,}717F$

$R_2 = 13{,}462\Omega$

The equation (5) of the mathematical model of the Supercapacitor were designed in MATLAB/Simulink using the obtained parameters. In this simulation, a constant current source is used in charging, zero current and discharging mode, to observe the voltage variations as shown in figure 4.

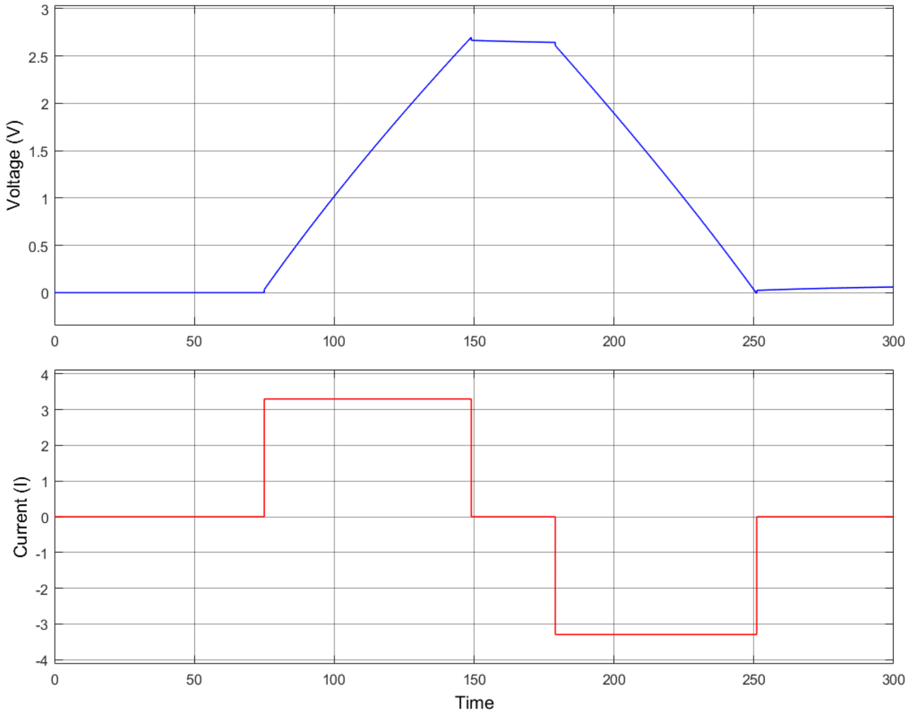

Fig.4. Voltage and current during charge and discharge simulation

Another simulation was done using a three-branch model with a parameter identified in a previous study to compare the two models, as show in figure 5 the voltage variations are almost similar which show that this model is simple and accurate.

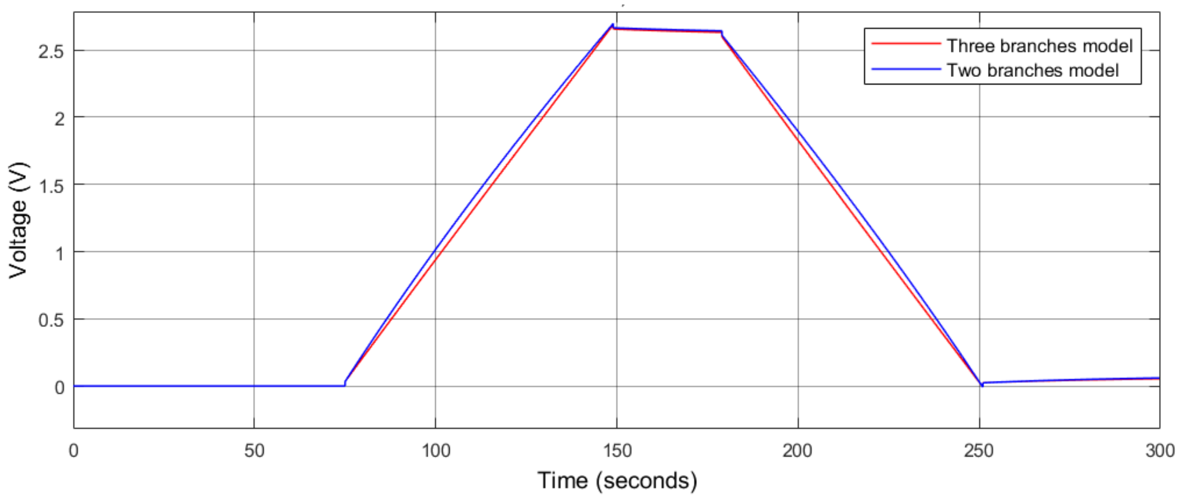

Fig.5. voltage of two and three-branch model simulation

The experimental charging profile of the supercapacitor is illustrated in figure 6.

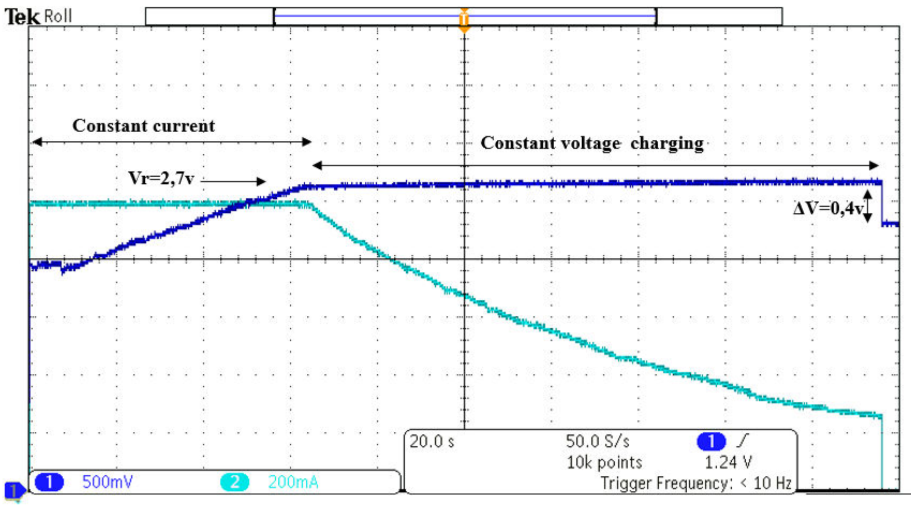

Fig. 6. Charging profile of supercapacitor

HYBRID ENERGY STORAGE SYSTEM

The hybrid energy storage system (HESS) integrates both batteries and supercapacitors to take advantage of each one. Batteries offer high energy density, making them suitable for sustained energy supply, while supercapacitors provide high power density, making them ideal for handling peak power demands and rapid charge/discharge cycles [2] [3, 4].

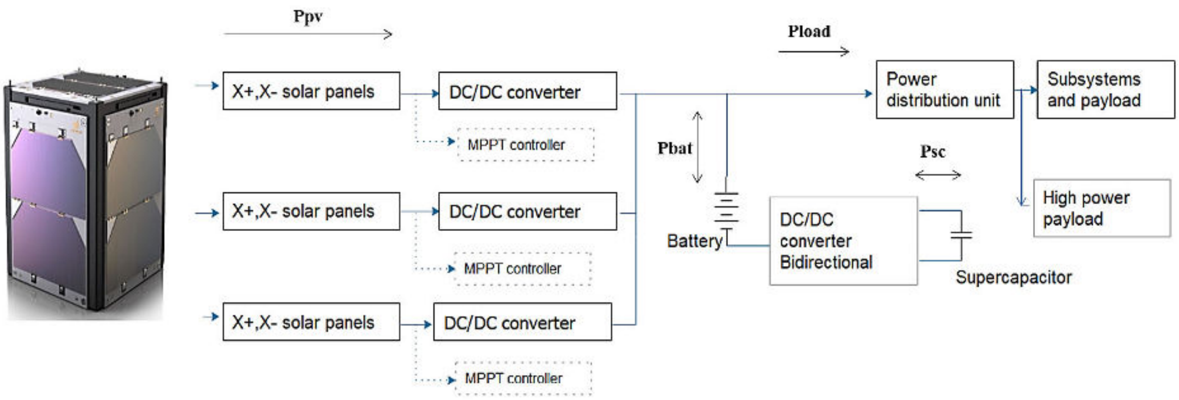

Fig. 7. Bloc diagram of the electrical power system.

A bloc diagram of the proposed architecture of HESS is shown in figure 7, it is designed to optimize energy distribution and storage efficiency [3, 5, 6]. The system includes:

- **Solar Cells:** For this proposed Nanosatellite, the triple-junction solar cells based on 3G30A technology InGaP/GaAs/Ge are selected, this space-qualified solar cells have an efficiency of 29.6%.the average power provided from the panels is 2.29Wh
- **Batteries:** The batteries used for this energy storage system are high power lithium Ion, their characteristics are summarized in Table 4.
- **Supercapacitors:** Used to manage peak power requirements and deliver instantaneous power during times of high load
- **Power Management Unit (PMU):** Guarantees optimal performance by managing the energy flow between batteries, supercapacitors, and solar cells [7-9].

The discharge characteristic of the used battery is shown in figure 8.

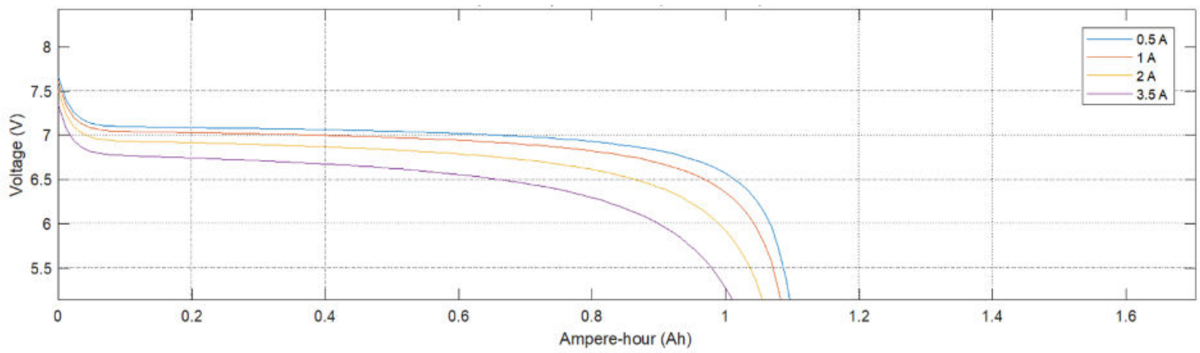

Fig.8. Simulation of discharge characteristic of the battery

Table 4. Lithium Ion Battery Characteristic

Nominal capacity and voltage	1.1Ah, 3.3 V
Recommended standard charge method	1.5A to 3.6V CCCV, 45 min
Recommended fast charge current	4A to 3.6V CCCV, 15 min
Maximum continuous discharge	30A
DOD Over	1,000 cycles
Recommended charge and cut-off V at 25°C	3.6V to 2V
Operating temperature range	-30°C to +60°C
Storage temperature range	-50°C to +60°C

A bidirectional DC/DC converter is used to interface the supercapacitor with the battery (figure 8), it charges the supercapacitor after mission execution and supply power to the nanosatellite subsystems.

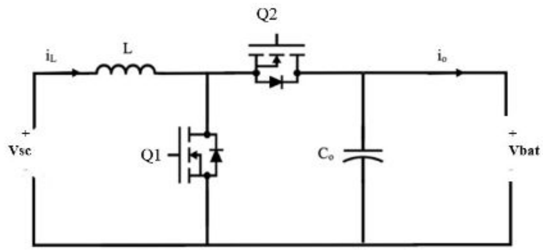

Fig. 8. Bidirectional DC/DC converter equivalent circuit

The converter works in two modes, each mode works by regulating the inductor's current. So, two switches are needed for this, each situation is managed independently depending on the conditions, if the power generation exceeds power consumption, the supercapacitor is charged. However, if the battery's current exceeds its rated value, the supercapacitor discharges or supplies energy to the nanosatellites subsystem as presented in the figure 9.

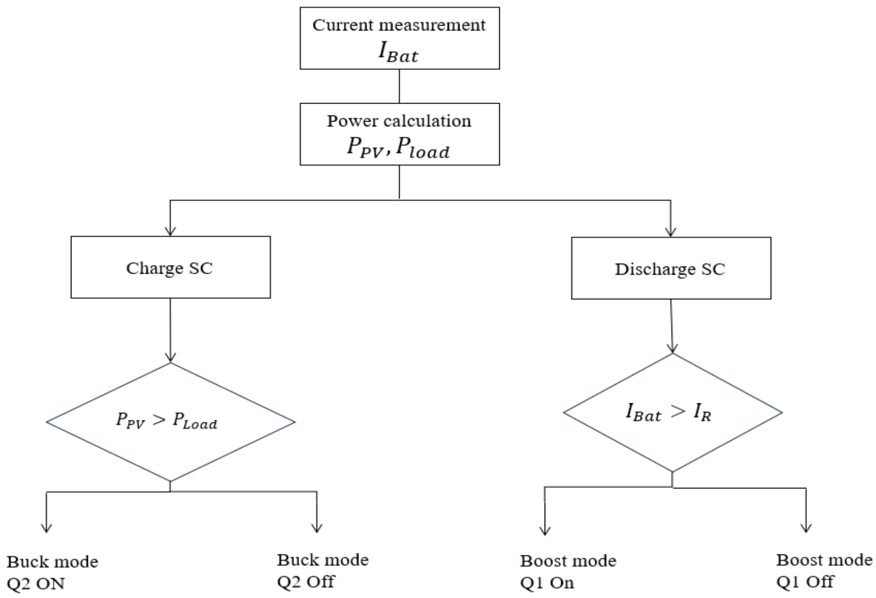

Fig. 9. Flowchart of the operational modes of the power management

The KCL and KVL equations are necessary to study the model. Since the circuit use two switches, the system can operate in four different ways. The supercapacitor supplies power to the subsystems with the batteries in the first and second modes.
In this instance, D2 is off while Q1 is ON. After that, Q1 switches OFF and D2 starts to run. During the operation of peak power loads, the inductor current is controlled by the switch Q1.
The supercapacitor is charged after the peak power load requirement. In this model, switch Q2 is controlled in two ways, allowing the supercapacitor to be charged during the sunlight period. This means that after turning switch Q2 while D1 is OFF, turn on D1 while Q2 is OFF. In this instance, the controller verifies that there is enough generated power to charge the supercapacitor by examining the load and comparing it to the generation profile.
The equations of the two modes are presented in table 5.

Table5. Bidirectional converter parameter expressions

Charging supercapacitor	Discharging supercapacitor
Q2 ON: $L\frac{di_L}{dt} = v_0 - v_{sc}$ $C_0\frac{dv_0}{dt} = i_0 - i_L$ Q2 OFF: $L\frac{di_L}{dt} = -v_{sc}$ $C_0\frac{dv_0}{dt} = i_0$	Q1 ON: $L\frac{di_L}{dt} = v_{sc}$ $C_0\frac{dv_0}{dt} = -i_0$ Q1 OFF: $L\frac{di_L}{dt} = v_{sc} - v_0$ $C_0\frac{dv_0}{dt} = i_L - i_0$

To evaluate the performance of the HESS, the model of the nanosatellite's power system presented in figure 7 is developed using MATLAB/Simulink. The power demand profile and the mission parameters are presented in the second section.

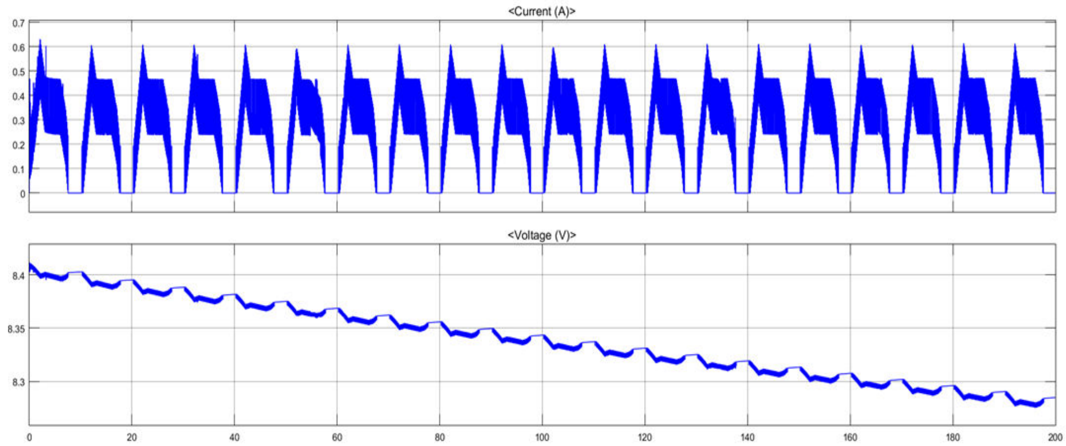

Fig.9: Current and voltage of the battery profile during mission mode.

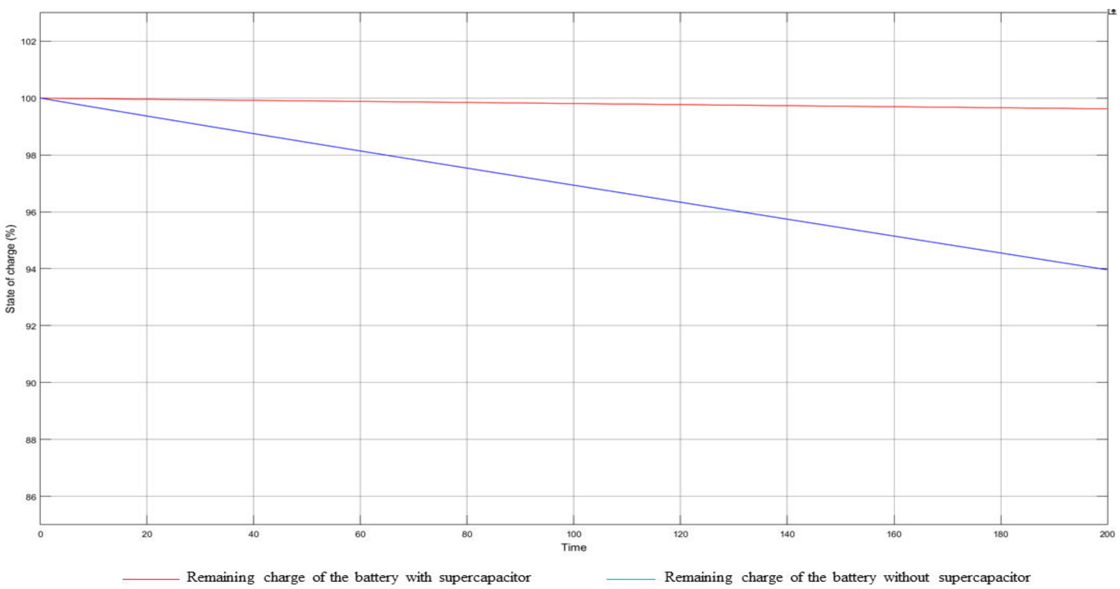

Fig 10. Comparison between state of charge of the battery with and without the supercapacitor

The variation in the battery charge level during the eclipse period when the electrical power system (EPS) is equipped with a supercapacitor (hybrid system), and when the EPS operates with battery only is shown in figure 10. In the EPS with the supercapacitor, the discharge of the battery is less deep that's means a longer battery life.

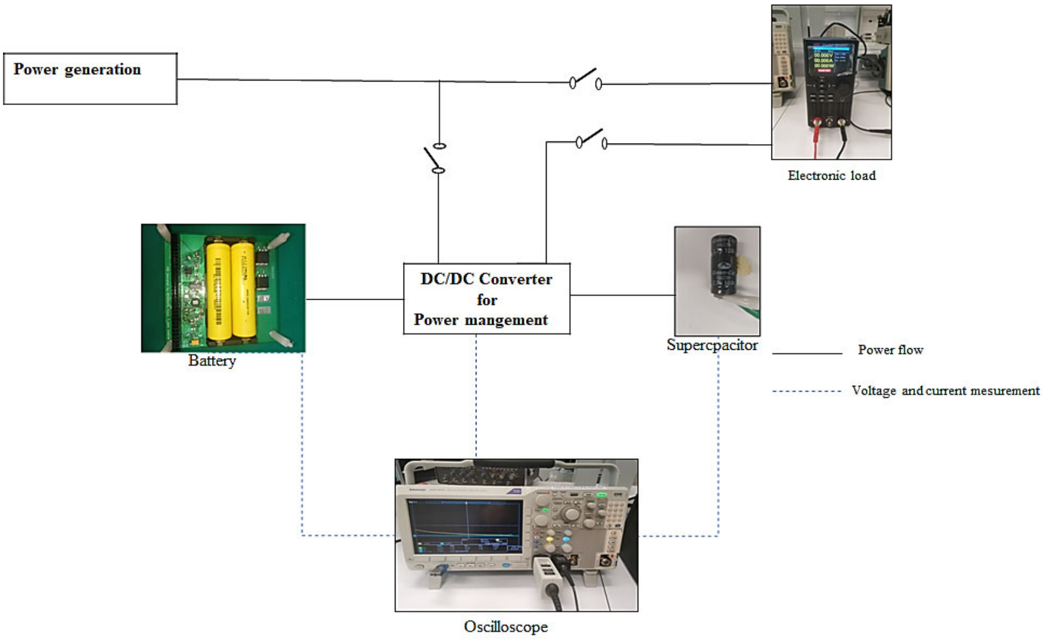

Fig. 11. Schematic block of hybrid energy storage experimental test.

In the experiment, a hybrid energy storage system (HESS) is implemented by integrating a supercapacitor and two batteries in series, managed by a DC/DC converter for optimized charge and discharge control as shown figure 11. This configuration was designed to extend battery life under varying demand conditions typical of satellite operations. To simulate high-power consumption, a programmable electronic load is employed, allowing to evaluate the system's response. the voltage and current response are shown in figure 12.
This setup tests the feasibility of integrating supercapacitors into satellite power architectures.

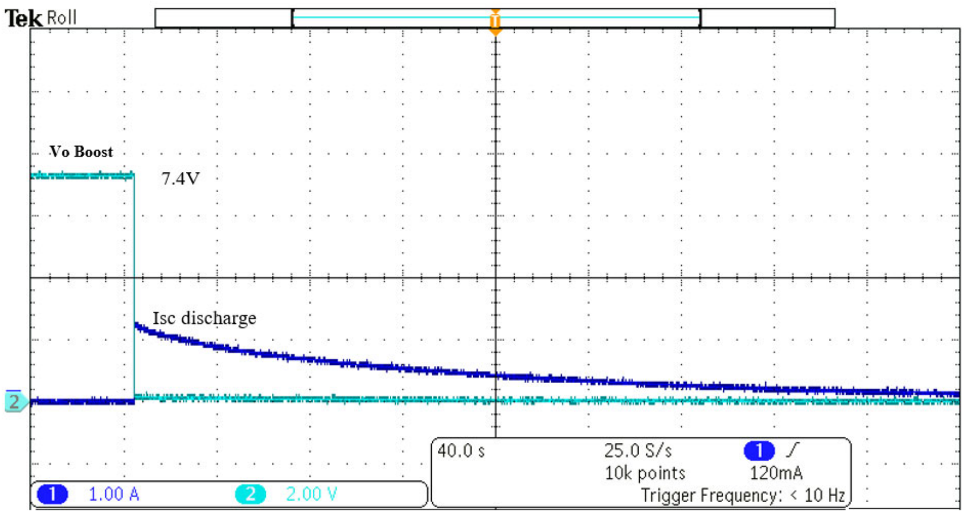

Figure 12: voltage and current across the converter

CONCLUSION

The objective of this paper was to demonstrate the benefits and drawbacks associated with integrating a Hybrid Energy Storage System (HESS) into a nanosatellite's power system. Initially, the energy requirements of a 1U nanosatellite mission were defined. Subsequently, a two-branch model was studied, and the parameters of the model were identified using an experimental setup. The procedure for this identification was presented, and the self-discharge issue was considered to highlight this drawback.

Finally, the integration of the supercapacitor into the hybrid system with the battery was discussed and testes experimentally. The results support the inclusion of the ultracapacitor as a storage system in addition to batteries for nanosatellite with peaky loads.

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